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(54) **TRANSMITTER AND RECEIVER CALIBRATION FOR OBTAINING THE CHANNEL RECIPROCITY FOR TIME DIVISION DUPLEX MIMO SYSTEMS**

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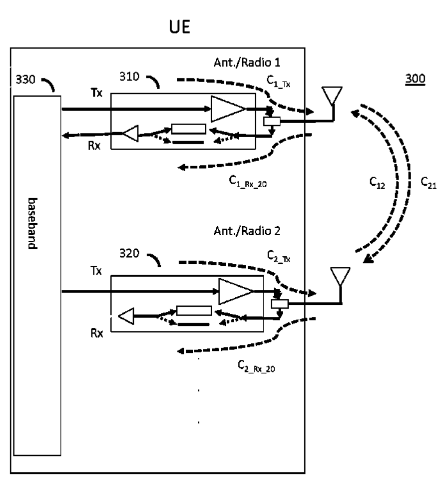
(57) **ABSTRACT**

A communication device operating in time division duplex (TDD) mode using multiple antennas is provided herein. The communication device uses receive channel estimation measurements to perform transmit beamforming and multiple input multiple output (MIMO) transmission, based on self-calibration of the various up/down paths via a method of transmission and reception between its own antennas, thus achieving reciprocity mapping between up and down links. Either user equipment (UE) or a base station may routinely perform this self-calibration to obtain the most current correction factor for the channel reciprocity to reflect the most current operating conditions present during TDD MIMO operation.

12 Claims, 6 Drawing Sheets



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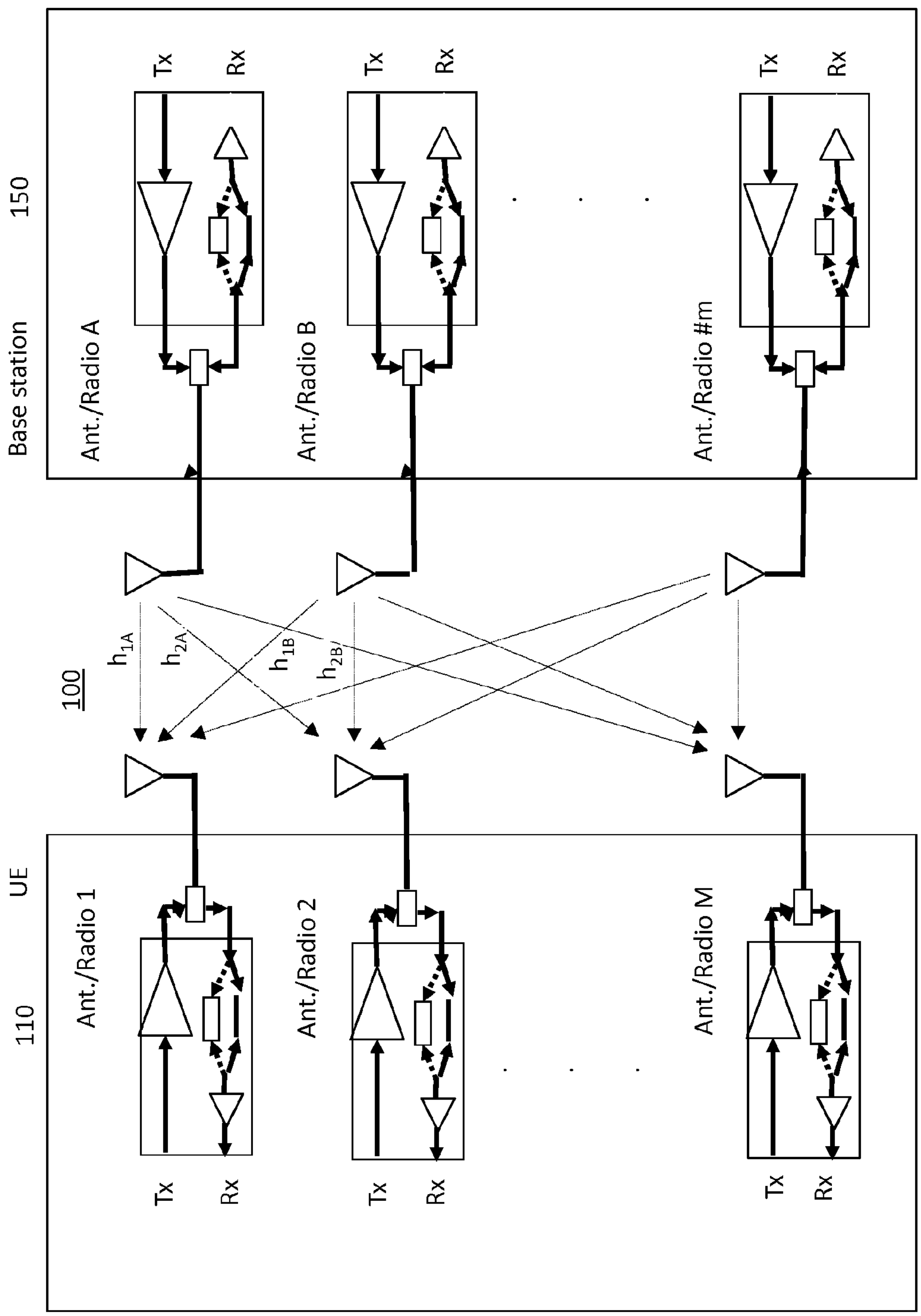
150
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Ant./Radio A
Ant./Radio B
Ant./Radio #m
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Rx
Tx
Rx
Tx
Rx
100
h_{1A}
h_{2A}
h_{1B}
h_{2B}
UE
110
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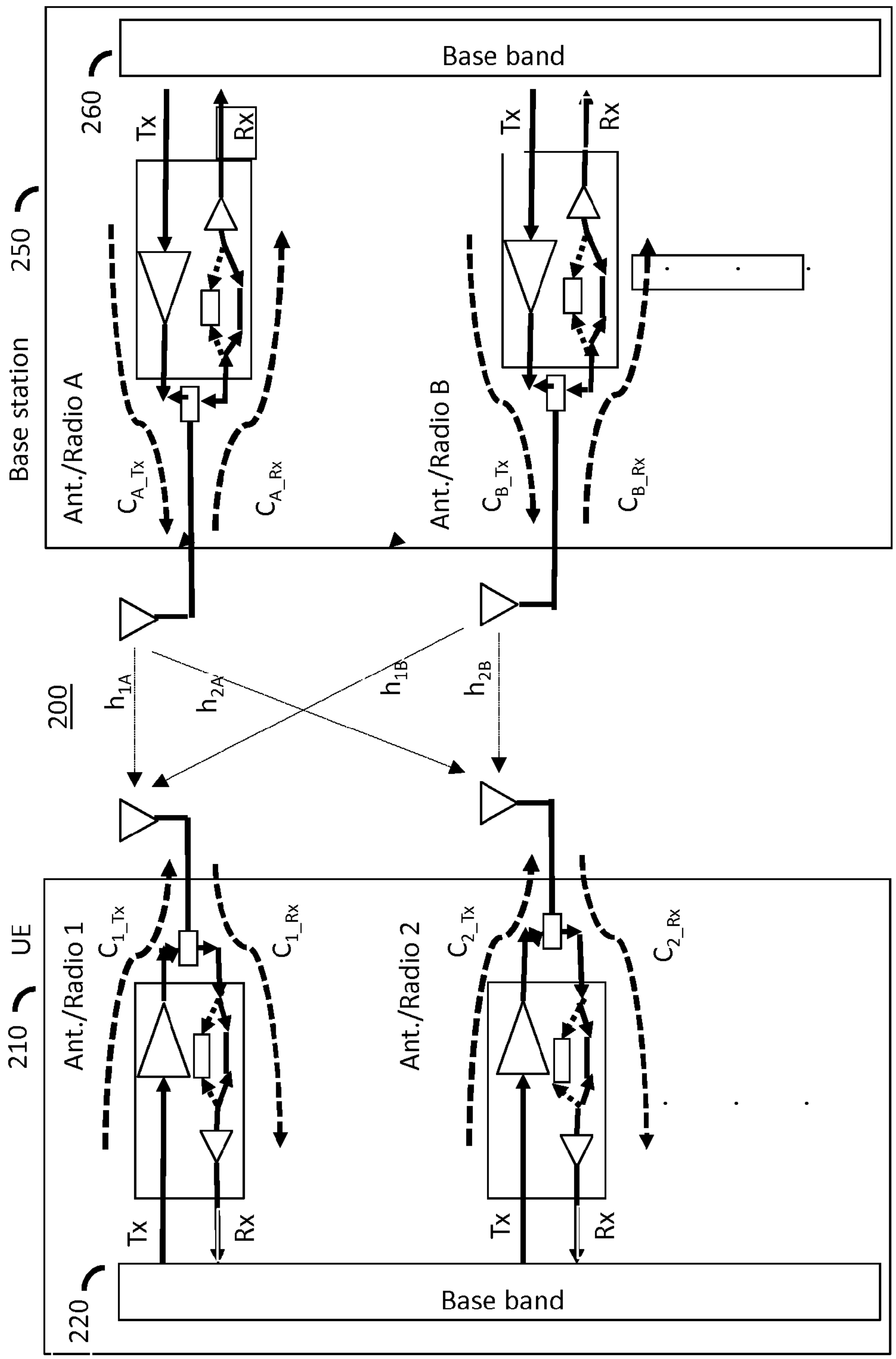
Ant./Radio 2
Ant./Radio M
Tx
Rx
Tx
Rx
Tx
Rx

Figure 1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250
260
Base band
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Rx
C_{A_Tx}
C_{A_Rx}
Ant./Radio B
Tx
Rx
C_{B_Tx}
C_{B_Rx}
200
h_{1A}
h_{2A}
h_{1B}
h_{2B}
UE
210
220
Ant./Radio 1
C_{1_Tx}
C_{1_Rx}
Tx
Rx
Ant./Radio 2
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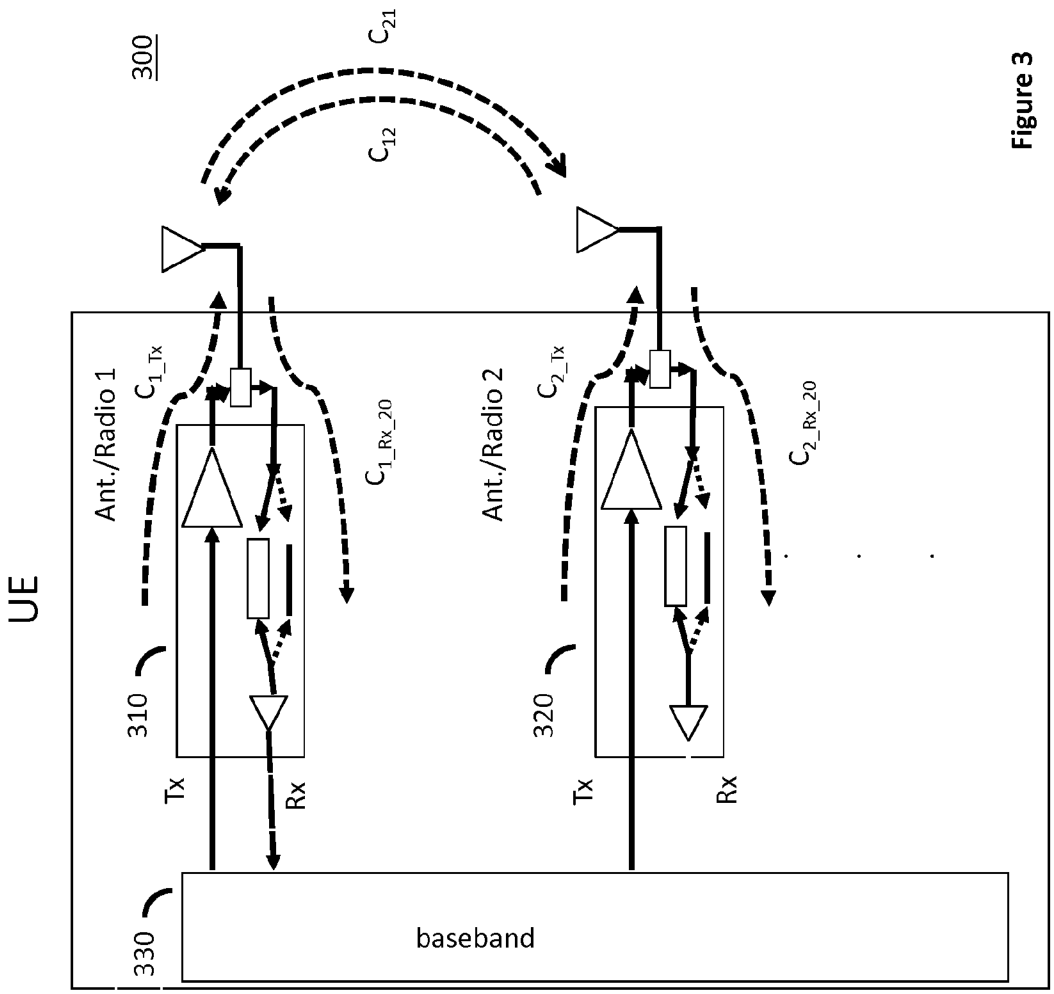
C_{2_Rx}
Tx
Rx
Base band

Figure 2


300
C_{21}
C_{12}
UE
Ant./Radio 1
C_{1_Tx}
$C_{1\_Rx\_20}$
Ant./Radio 2
C_{2_Tx}
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310
320
Tx
Rx
Tx
Rx
330
baseband

Figure 3

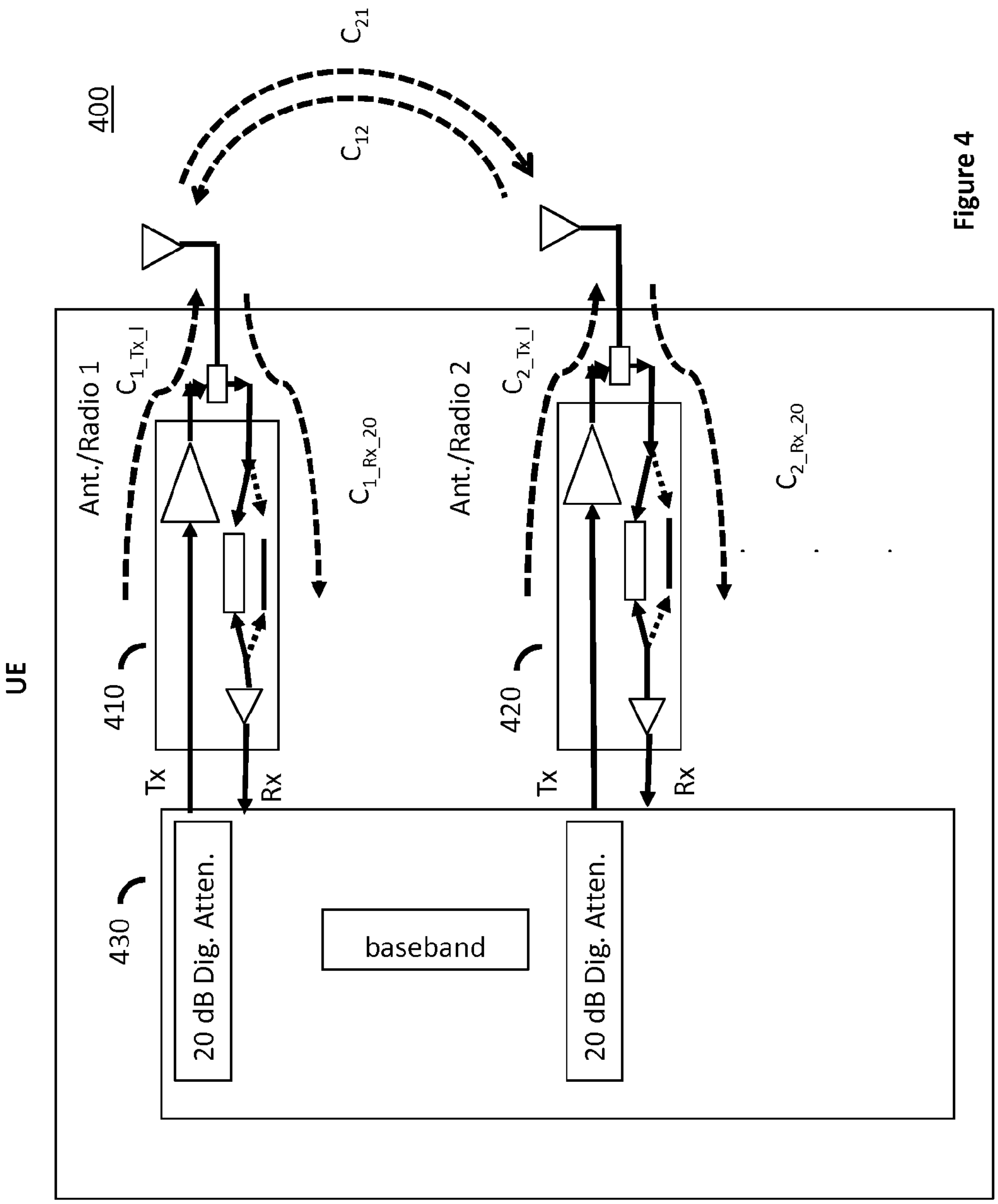
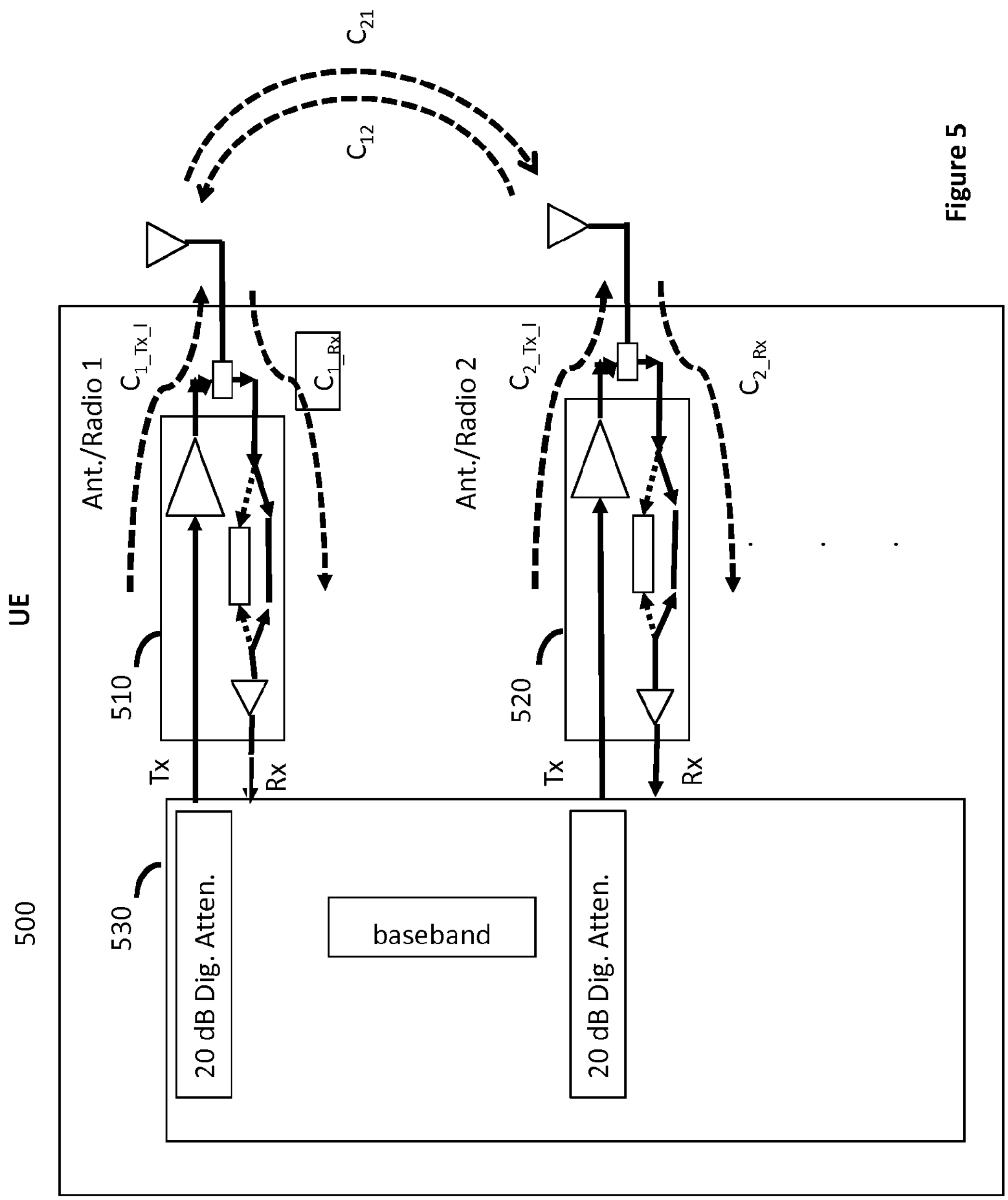
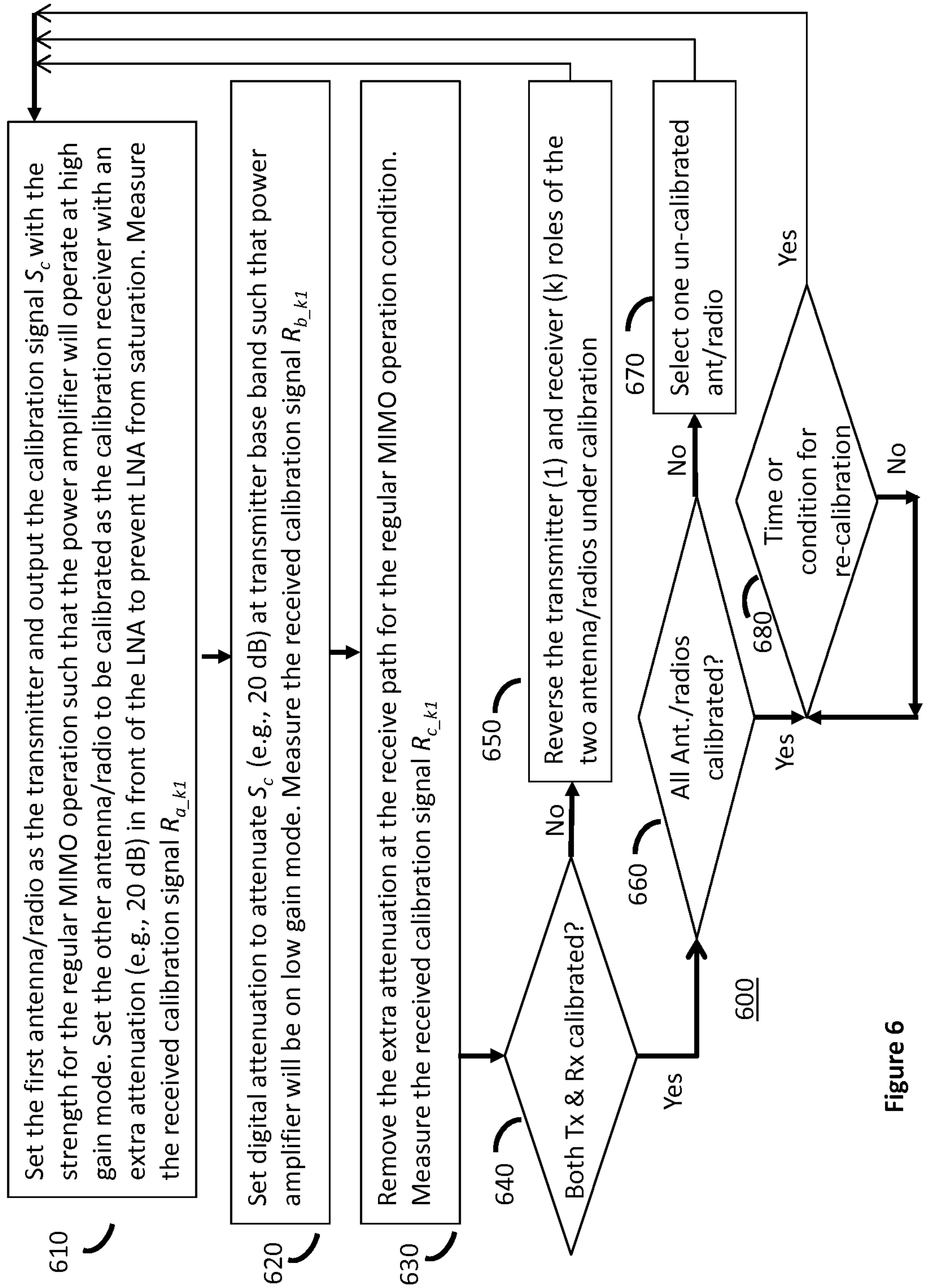

400
C_{21}
C_{12}
Ant./Radio 1
$C_{1\_Tx\_I}$
$C_{1\_Rx\_20}$
Ant./Radio 2
$C_{2\_Tx\_I}$
$C_{2\_Rx\_20}$
UE
410
420
430
Tx
Rx
Tx
Rx
20 dB Dig. Atten.
20 dB Dig. Atten.
baseband

Figure 4



UE
500
C21
C12
Ant./Radio 1
C1_Tx_I
C1_Rx
510
Tx
Rx
Ant./Radio 2
C2_Tx_I
C2_Rx
520
Tx
Rx
530
20 dB Dig. Atten.
baseband
20 dB Dig. Atten.

Figure 5


610
Set the first antenna/radio as the transmitter and output the calibration signal S_c with the strength for the regular MIMO operation such that the power amplifier will operate at high gain mode. Set the other antenna/radio to be calibrated as the calibration receiver with an extra attenuation (e.g., 20 dB) in front of the LNA to prevent LNA from saturation. Measure the received calibration signal R_{a_k1}
620
Set digital attenuation to attenuate S_c (e.g., 20 dB) at transmitter base band such that power amplifier will be on low gain mode. Measure the received calibration signal R_{b_k1}
630
Remove the extra attenuation at the receive path for the regular MIMO operation condition. Measure the received calibration signal R_{c_k1}
640
Both Tx & Rx calibrated?
Yes
No
650
Reverse the transmitter (1) and receiver (k) roles of the two antenna/radios under calibration
660
All Ant./radios calibrated?
Yes
No
670
Select one un-calibrated ant/radio
680
Time or condition for re-calibration
Yes
No
600
Figure 6

TRANSMITTER AND RECEIVER CALIBRATION FOR OBTAINING THE CHANNEL RECIPROCITY FOR TIME DIVISION DUPLEX MIMO SYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. patent application Ser. No. 14/109,904, filed on Dec. 17, 2013, which claims the benefit of U.S. Provisional Patent Application No. 61/906,157, filed on Nov. 19, 2013, all of which are incorporated in their entirety herein by reference.

FIELD OF THE INVENTION

The present invention relates to the transmitter and receiver calibration to obtain the channel reciprocity for multiple-input-multiple-output (MIMO) systems as well as for SISO and MISO systems, in which the transmit and receive operate in the same spectrum (for example, TDD, WiFi,) so that the feedback of channel state information can be reduced or eliminated for the MIMO operation. Here "time division duplex" (TDD) for the wireless communication systems is referred to in general for systems using the same frequency spectrum for methods of communications in a time division manner.

BACKGROUND OF THE INVENTION

Prior to setting forth a short discussion of the related art, it may be helpful to set forth definitions of certain terms that will be used hereinafter.

The term "MIMO" as used herein, is defined as the use of multiple antennas at both the transmitter and receiver to improve communication performance. MIMO offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It achieves this goal by spreading the transmit power over the antennas to achieve spatial multiplexing that improves the spectral efficiency (more bits per second per Hz of bandwidth) or to achieve a diversity gain that improves the link reliability (reduced fading), or increased antenna directivity.

The term "TDD" (Time Division Duplex) as used herein, is defined as the use of the same or a single channel (e.g., the same or overlapping frequency spectrum) for both downlink and uplink transmissions. For example, TDD communication, e.g., between a mobile device and a base station, may periodically alternate between uplink transmissions (e.g. from the mobile device to a base station for a predetermined uplink interval or period, such as, 5 milliseconds (ms)) and downlink transmissions (e.g. from a base station to a mobile device or UE for a predetermined downlink period, such as, 5 ms). The base station typically coordinates the alternating timing between uplink (UL) and downlink (DL) transmissions.

The term "beamforming" sometimes referred to as "spatial filtering" as used herein, is a signal processing technique used in antenna arrays for directional signal transmission or reception. This is achieved by combining elements in the array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity.

The term "beamformer" as used herein refers to RF circuitry that implements beamforming and usually includes a combiner and may further include switches, controllable phase shifters, and in some cases amplifiers and/or attenuators.

A transmitter in a MIMO system requires channel state information (CSI) so that a set of precoded weights can be set to the multiple data streams of the transmitter, in order to exploit the channels for the multiple spatial channel transmission. Typically, the receiver can feed the CSI or even the preferred pre-coding matrix (index) back to the transmitter. These feedbacks can consume some available bandwidth of the transmission in the opposite direction and reduce the data throughput. If transmission in both directions operate in the same spectrum, like in the case of time division duplex (TDD) systems, the channels through the air are reversible and the channel information can be estimated by the receive device and then applied to the transmit device.

However, a complete transmission channel should be from the transmitter baseband to the receiver baseband, which includes various components inside the transmitter (e.g., DAC, up converter, power amplifier, filter) and receiver (e.g., duplexer, LNA, down converter, filter, ADC). The transmission path and receive path may thus experience very different gain/loss and delays behavior, due to the different components used in both paths. Channel reciprocity without considering the different delay and gain/loss factors between the transmit/receive paths are therefore not valid and may not be accurate enough for the use by devices in TDD MIMO systems. These parameters can also be factory calibrated. One important element that jeopardizes reciprocity is antennas, which project slightly different radiation patterns at Up and Down Links, due to differences in the Voltage Standing Wave Ratio (VSWR) in both directions. Antenna VSWR cannot be practically calibrated in the factory, due to the cost of such procedures.

In beamforming applications there are benefits in using uplink signals' channel estimation for downlink beamforming, i.e. for establishment of calculated reciprocity A method and apparatus for self-calibration of the transmitter and receiver paths is disclosed herein (between base band and transmit/receive antennas) of a MIMO device to obtain the precise channel reciprocity information necessary for improving the (TDD) MIMO systems.

SUMMARY OF THE INVENTION

There is now provided according to embodiments of the invention a calibration method to improve TDD MIMO system for effectively overcoming the aforementioned difficulties inherent in the art.

According to an embodiment of the invention, communication devices are provided in a MIMO system. The communication device may be static such as a base station, or may be mobile such as user equipment (UE). The communication device may include a plurality of M antennas for TDD MIMO operation. Each antenna may be used for both transmit and receive paths. The communication device may include switches to provide extra paths in the receiving path of each radio. One of the multiple receiving paths will be implemented via the path used for the regular operation. Another receiving path may consist of an attenuator to provide an additional path loss (for example, 20 dB) so that the Low Noise Amplifier (LNA) will not be saturated by the strong calibration signal during the calibration process.

According to some embodiments of the present invention, the communication device may perform the following self-calibration processes to obtain the correction factor for the channel reciprocity information. A communication device may transmit the calibration signals from one antenna/radio while itself measures the calibration signals through another antenna/radio under three calibration configuration setups: (A) the calibration signals are transmitted in high power mode (at maximum output power allowed), the receive path should include an attenuator (e.g., 20 dB attenuation) in front of the LNA to safe guard the LNA, (B) the calibration signal is transmitted in lower power mode (e.g., digitally attenuated by 20 dB), the receive path includes the extra attenuation (such as, in a non-limiting example, 20 dB), and (C) the calibration signal is transmitted in lower power mode while the receive path is through the path used in the normal operation mode. The received calibration signals in these three calibration setups can then derive the correction factor between these two antennas to account for the channel reciprocity information. This calibration process may be repeated for all the antennas to be used in MIMO transmit and receive. Both transmit and receive radio paths of each antenna should be calibrated at least once. For example, we may pair each of the M−1 antennas with the first antenna for two calibrations (one transmit, one receive). With (2M−2) calibrations, we may get all the correction factors for the devices consisting of M antennas/radios.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, both as to organization and method of operation, together with objects, features, and advantages thereof, may best be more fully understood by reference to the following detailed description when read with the accompanying drawings in which:

FIG. **1** is a schematic illustration of channel description for a TDD MIMO system according to some embodiments of the present invention;

FIG. **2** is a schematic illustration of effective channel including the transmit and receive paths for channel reciprocity according to some embodiments of the present invention;

FIG. **3** depicts an exemplary UE self-calibration configuration for Step (a) according to some embodiments of the present invention;

FIG. **4** illustrates an exemplary UE self-calibration configuration for Step (b) according to some embodiments of the present invention;

FIG. **5** shows an exemplary UE self-calibration configuration for Step (c) according to some embodiments of the present invention; and

FIG. **6** describes the logic flow contained in the self-calibration procedure according to some embodiments of the present invention.

It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, various aspects of the present invention will be described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the present invention. However, it will also be apparent to one skilled in the art that the present invention may be practiced without the specific details presented herein. Furthermore, well known features may be omitted or simplified in order not to obscure the present invention.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "processing," "computing," "calculating," "determining," or the like, refer to the action and/or processes of a computer or computing system, or similar electronic computing device, that manipulates and/or transforms data represented as physical, such as electronic, quantities within the computing system's registers and/or memories into other data similarly represented as physical quantities within the computing system's memories, registers or other such information storage, transmission or display devices.

Embodiments of the present invention propose the calibration configurations and procedures to derive the correction factors on channel reciprocity information to make this information useful for improving the spectral efficiency in TDD MIMO systems.

According to some embodiments of the present invention, a communication device having a receive path is provided. The communication device may include a number M antennas and respective radio modules. The communication device may further include a processor operable in a baseband domain and configured to perform a self-calibration procedure by which a correction factor may be computed for a channel reciprocity level, determined by said self-calibration procedure. The communication device may further include a plurality of switches in each one of said radio modules configured to change the receive path for regular multiple-input multiple-output (MIMO) operation or during the aforementioned calibration procedure. The communication device may further include a digital attenuator configured to adjust calibration signals in the baseband domain, wherein the communication device may be operative in a time division duplex (TDD) MIMO system.

According to some embodiments of the present invention, the communication device may further include an antenna set that may be configured to alternate transmitting and receiving periods on a single channel according to a TDD communication protocol, wherein the aforementioned antenna set may be used for defining the phases employed in MIMO transitions and selected using information measured at the device during receiving periods based on channel reciprocity.

According to some embodiments of the present invention, the communication device may further include means for supporting N×N MIMO transmissions and receptions, such that M≥N.

According to some embodiments of the present invention, the communication device may further include multiple receive paths and a plurality of switches contained in the device, wherein some path losses included in the receive path between the receive antenna and a low noise amplifier (LNA); and switches which may change the receive paths used during regular MIMO operation and during calibration.

According to some embodiments of the present invention, the communication device may further include processor or other baseband logic for digitally attenuating the calibration signal by an amount that is sufficient to prevent the LNA in the path undergoing calibration from saturating.

According to some embodiments of the present invention, the communication device may further include a processor or other baseband logic performing the self-calibration procedure, in order to adjust for the differences in the transmit path and receive path for all the antenna/radios used in MIMO operation, wherein the correction factors are expressed by ρ_{ij}, which is the ratio of the differences between the transmit and receive paths contained in the antenna/radio j and antenna/radio i for channel reciprocity.

According to some embodiments of the present invention, the communication device may be further configured to perform the following self-calibration procedure in which one antenna/radio (i) acts as a transmitter and the other antenna/radio (j) acts as the receiver during the calibration procedure: performing the following for each two antennas/radios (i and j): selecting using a processor or other baseband logic two antennas/radios (i and j) for the following 3-step self-calibration procedure; emitting a calibration signal with the signal strength equivalent to the signal strength used during regular MIMO operation, the receiver using one receive path with some path loss to prevent LNA from saturation and recording the received calibration signal R_{a_ji}; transmitting a calibration signal that is digitally attenuated, the receiver continually employing the same receive path used in said emitting step and recording the received calibration signal R_{b_ji}; transmitting a calibration signal that is digitally attenuated, the receiver switch selecting the receive path used for regular MIMO operation and recording the received calibration signal R_{c_ji}; and reversing the roles of transmitter and receiver for the two selected antennas/radios to repeat said self-calibration procedure and recording the three measured calibrated signals R_{a_ij}, R_{b_ij}, and R_{c_ij}.

According to some embodiments of the present invention, the communication device may be further operable to compute the correction factor on channel reciprocity by: performing the following for a calibrated antenna/radio and un-calibrated antenna/radio pair: selecting using a processor or other baseband logic a calibrated and un-calibrated pair to perform the 3-step calibration procedure after completing the calibration for the first pair; and repeating the calibration process until all the antennas/radios to be used for MIMO operations are all calibrated.

According to some embodiments of the present invention, the communication device may be further operable to compute the correction factor on channel reciprocity by: using the processor or other baseband logic to determine the correction factor on channel reciprocity obtained with the calibration data for antenna/radio elements i and j, wherein said correction factor is expressed by $\rho_{ij}=(R_{a\_ji}*R_{c\_ji}*R_{b\_ij})/(R_{b\_ji}*R_{a\_ij}*R_{c\_ij})$.

According to some embodiments of the present invention, the communication device may further include: a timer; and said timer operable to be preset using said processor or other baseband logic to repeat the 3-step calibration procedure for all the antennas/radios to be used for MIMO operation by re-computing and updating the correction factors for channel reciprocity.

According to some embodiments of the present invention, the communication device may be further operable to re-compute said correction factors for channel reciprocity based on the threshold of a changing condition by: presetting said processor or other baseband logic to re-compute and update the correction factors for channel reciprocity when said threshold is met; and repeating the 3-step calibration procedure for all the antennas/radios to be used for MIMO operation.

FIG. **1** illustrates a TDD MIMO system. Element **110** shows that the UE has M antennas and radios. Element **150** illustrates that the base station may also have M antennas and radios as well. Each antenna on these two devices may be used for both transmit and receive, but not simultaneously, in the TDD MIMO operation. The channels available over the air (between the antennas) are reversible, i.e., $h_{1A}=h_{A1}$,

$h_{2A}=h_{A2}$, $h_{1B}=h_{B1}$, . . . , $h_{1M}=h_{M1}$. However, the MIMO signals are processed in the base band shown in elements **220** and **260** contained in FIG. **2**. Hence, the effective channels considered for reciprocity should include the transmit path and the receive path of both communication devices (e.g., both base station and UE). As shown in FIG. **2**, the effective channels $\tilde{h}_{1A}$, $\tilde{h}_{2A}$, $\tilde{h}_{1B}$, and $\tilde{h}_{2B}$, can then be expressed by the following equations:

$$\tilde{h}_{1A}=C_{A\_Tx}*h_{1A}*C_{1\_Rx} \tag{1}$$

$$\tilde{h}_{2A}=C_{A\_Tx}*h_{2A}*C_{2\_Rx} \tag{2}$$

$$\tilde{h}_{1B}=C_{B\_Tx}*h_{1B}*C_{1\_Rx} \tag{3}$$

$$\tilde{h}_{2B}=C_{B\_Tx}*h_{2B}*C_{2\_Rx} \tag{4}$$

where C_A and C_B are the gains/loss of the transmitters, and C_1 and C_2 are the gains/loss of the receivers.

In the exemplary TDD MIMO system shown in FIG. **2**, the UE may perform a self-calibration, according to the embodiments of the present invention, to obtain the correction factor for obtaining the valid uplink channel information ($\tilde{h}_{A1}$, $\tilde{h}_{A2}$, $\tilde{h}_{B1}$, and $\tilde{h}_{B2}$) from its estimated downlink receiving channels ($\tilde{h}_{1A}$, $\tilde{h}_{2A}$, $\tilde{h}_{1B}$, and $\tilde{h}_{2B}$), those may be used to calculate the pre-coding weights for the UE's MIMO transmission.

According to one embodiment of this invention, the base station may perform a self-calibration process, to obtain the correction factor for the channel reciprocity so that the base station may apply the channel reciprocity to obtain the down link channel information from the estimated channels.

According to another embodiment of this invention, the self-calibration of a communication device is performed to determine the difference between the transmit path and receive path of each radio. This calibration may be done using its own two antennas/radios, one for transmit and the other for receive. The calibration process may be repeated until both transmit and receive paths for all the antennas/radios are calibrated. The calibration is done for the regular operation condition (i.e., power amplifiers operating in high power mode, and by low noise amplifiers in the receive paths that are not saturated.). The high power PA transmission may saturate the receiving LNA during the calibration since the transmit antenna/radio and the receive antenna/radio may be next to each other (i.e. in the same communication device). The extra attenuation path may be provided in the receive path to prevent the LNA from saturation during the calibration. The calibration process may be separated into three steps with three different calibration configurations (modes) to get rid of the impact of the extra attenuations/paths effects on the calibration.

FIG. **3** shows the configuration setup for the first step (a) of the calibration. The calibration signal S_c, is output from baseband element **330**, and is transmitted from the first antenna/radio **310** with the nominal maximum power allowed in the regular operation. The calibration signal may be received, through antenna coupling C_{21}, by the second antenna/radio **320**. For Step (a) calibration, an extra attenuation (e.g., 20 dB) may be set in the receive path to prevent the LNA from saturating. The received calibration signal R_{a_21} at the base band can then be expressed by:

$$R_{a\_21}=S_c*C_{1\_Tx}*C_{21}*C_{2\_Rx\_20} \tag{5}$$

wherein C_{1_Tx} is the gain/loss of the transmit path between the baseband and the first antenna when the power amplifier operates in high-power mode, C_{21} is the antenna coupling from transmit antenna (1) to receive antenna (2), and

$C_{2\_Rx\_20}$ is the gain/loss of the receive path between the second antenna and the baseband including the additional attenuation.

Here the extra attenuation of 20 dB is assumed during the Step (a) calibration. Note that the power amplifiers in MIMO transmission usually operate at high gain mode to support the high data rate communications.

400 (FIG. **4**) shows the configuration setup for the second step (b) of the calibration. The calibration signal S_c, digitally attenuated by 20 dB and output from baseband **430**, is transmitted from the first antenna/radio **410**. The calibration signal may be received, through antenna coupling C_{21}, by the second antenna/radio **420**. For Step (b) calibration, an extra attenuation (e.g., 20 dB) may be kept in the receive path. The received calibration signal R_{b_21} at the base band can then be expressed by:

$$R_{b\_21}=S_c*C_{1\_Tx\_l}*C_{21}*C_{2\_Rx\_20}/10 \tag{6}$$

Wherein $C_{1\_Tx\_l}$ is the gain/loss of the transmit path between the baseband and the first antenna when the power amplifier operates in low-power mode. It should be noted that the division by 10 on the right hand side of Equation (6) indicates the calibration signal S_c power being digitally attenuated by 20 dB.

FIG. **5** shows the configuration setup for the third step (c) of the calibration. The calibration signal S_c, is digitally attenuated by 20 dB and output from baseband element **530**, and is transmitted from the first antenna/radio **510**. The calibration signal may be received, through antenna coupling C_{21}, by the second antenna/radio **520**. For step (c) calibration, the receive path is kept under the regular operation condition without the extra attenuation. The received calibration signal R_{c_21} at the baseband can then be expressed by:

$$R_{c\_21}=S_c*C_{1\_Tx\_l}*C_{21}*C_{2\_Rx}/10 \tag{7}$$

Where C_{2_Rx} is the gain/loss of the receive path between the second antenna and the baseband under regular operation (i.e., excluding the extra attenuation).

Equation (5), (6), and (7) consist of the information of the transmit path of the first antenna/radio, C_{1_Tx}, and the receive path of the second antenna/radio, C_{2_Rx}, that are needed for deriving the correction factors on the channel reciprocity. The 3-step calibration may be repeated with the reverse of calibration signal transmission, i.e., the calibration signal is transmitted from the second antenna/radio and received by the first antenna/radio. The latter calibration will obtain the information of the receive path of the first antenna/radio, C_{1_Rx}, and the transmit path of the second antenna/radio, C_{2_Tx}, and can be expressed by the following equations, Eq. (8), (9) and (10):

$$R_{a\_12}=S_c*C_{2\_Tx}*C_{12}*C_{1\_Rx\_20} \tag{8}$$

$$R_{b\_12}=S_c*C_{2\_Tx\_l}*C_{12}*C_{1\_Rx\_20}/10 \tag{9}$$

$$R_{c\_12}=S_c*C_{2\_Tx\_l}*C_{12}*C_{1\_Rx}/10 \tag{10}$$

Wherein C_{2_Tx} is the gain/loss of the transmit path between the baseband and the second antenna for power amplifier operating at high gain mode (regular MIMO operation), $C_{2\_Tx\_l}$ is the gain/loss of the transmit path between the baseband and the second antenna when the power amplifier operates at low-power mode, $C_{1\_Rx\_20}$ is the gain/loss of the receive path between the second antenna and the baseband including the extra attenuation (e.g., 20 dB). C_{1_Rx} is the gain/loss of the receive path between the first antenna and the baseband under regular operation (i.e., excluding the extra attenuation).

In addition, the antenna coupling is reversible, i.e., $C_{21}=C_{12}$.

In the exemplary TDD 2×2 MIMO system, the UE may perform channel estimation and obtain the downlink channel information, $\tilde{h}_{1A}$, $\tilde{h}_{2A}$, $\tilde{h}_{1B}$, and $\tilde{h}_{2B}$, represented by Eq. (1), (2), (3), and (4), respectively. The UE may utilize the channel reciprocity to obtain the uplink MIMO transmission channels so that the UE can set up the pre-coding weights accordingly. The uplink MIMO channels, $\tilde{h}_{A1}$, $\tilde{h}_{A2}$, $\tilde{h}_{B1}$, and $\tilde{h}_{B2}$ can be expressed by the following equations Eq. (11), (12), (13), and (14):

$$\tilde{h}_{A1}=C_{1\_Tx}*h_{A1}*C_{A\_Rx} \tag{11}$$

$$\tilde{h}_{A2}=C_{2\_Tx}*h_{A2}*C_{A\_Rx} \tag{12}$$

$$\tilde{h}_{B1}=C_{1\_Tx}*h_{B1}*C_{B\_Rx} \tag{13}$$

$$\tilde{h}_{B2}=C_{2\_Tx}*h_{B2}*C_{B\_Rx} \tag{14}$$

Where h_{A1}, h_{A2}, h_{B1}, and h_{B2} are the uplink MIMO channels from UE Tx antennas to the receive antennas of the base station. These over the air channels are reversible, i.e., $h_{1A}=h_{A1}$, $h_{2A}=h_{A2}$, $h_{1B}=h_{B1}$, and $h_{2B}=h_{B2}$.

On the uplink MIMO transmission, there is a correction factor between the Tx antennas of the UE, due to the difference between the Tx/Rx paths of the UE antennas/radios. These correction factors may be derived from the calibration. In the exemplary 2×2 MIMO configuration, the correction factor between the first and second Tx antenna may be explicitly obtained. Staring with Eq. (11) and (12), that represent the channels from the first and second Tx antennas of the UE to the receive antenna A at base station, this can be expressed by:

$$\tilde{h}_{A1}/\tilde{h}_{A2}=(C_{1\_Tx}*h_{A1})/(C_{2\_Tx}*h_{A2}) \tag{15}$$

Similarly, from Eq. (1) and (2), we may obtain:

$$\tilde{h}_{1A}/\tilde{h}_{2A}=(C_{1\_Rx}*h_{1A})/(C_{2\_Rx}*h_{2A}) \tag{16}$$

The on the air channels are reversible ($h_{A1}=h_{1A}$, $h_{A2}=h_{2A}$). From Eq. (15) and (16), the ratio of the uplink MIMO channels for the two transmit antennas may be represented in Eq. (17),

$$\tilde{h}_{A1}/\tilde{h}_{A2}=(\tilde{h}_{1A}/\tilde{h}_{2A})*(C_{1\_Tx}*C_{2\_Rx})/(C_{2\_Tx}*C_{1\_Rx})=(\tilde{h}_{1A}/\tilde{h}_{2A})*\rho_{12} \tag{17}$$

Note that $\tilde{h}_{1A}$ and $\tilde{h}_{2A}$ may be obtained from UE's channel estimation, and the correction factor $\rho_{12}=(C_{1\_Tx}*C_{2\_Rx})/(C_{2\_Tx}*C_{1\_Rx})$ in which C_{1_Tx}, C_{2_Rx}, C_{2_Tx}, and C_{1_Rx} may be obtained from the invented 3-step calibrations. Similarly, using Eq. (3), (4), (13), and (14), the other two channels to the receive antennas B at the base station may be shown with the same correction factor, i.e.:

$$\tilde{h}_{B1}/\tilde{h}_{B2}=(\tilde{h}_{1B}/\tilde{h}_{2B})*(C_{1\_Tx}*C_{2\_Rx})/(C_{2\_Tx}*C_{1\_Rx})=(\tilde{h}_{1B}/\tilde{h}_{2B})*\rho_{12} \tag{18}$$

Equations (17) and (18) show that the uplink channel may be obtained from the downlink channel estimation and the correction factor, ρ_{12}, which is the weight (amplitude and phase) ratio of antenna 1 to antenna 2.

Furthermore, from Equation (5), (6), and (7), the following formula may be obtained:

$$C_{1\_Tx}*C_{2\_Rx}=(R_{a\_21}*R_{c\_21})/(R_{b\_21}*S_c*C_{21}) \tag{19}$$

Similarly, the following may be obtained from Eq. (8), (9), and (10):

$$C_{2\_Tx}*C_{1\_Rx}=(R_{a\_12}*R_{c\_12})/(R_{b\_12}*S_c*C_{12}) \quad (20)$$

Coupling between the antennas are reversible (i.e., $C_{21}=C_{12}$). The correction factor for the channel reciprocity, ρ_{12}, may then be obtained from the 3-step self-calibration measurement,

$$\rho_{12}=(R_{a\_21}*R_{c\_21}*R_{b\_12})/(R_{b\_21}*R_{a\_12}*R_{c\_12}) \quad (21)$$

According to another embodiment of this invention a TDD communication device (either a UE or a base station) may routinely perform this self-calibration to obtain the most current correction factor for the channel reciprocity to reflect the most current operating conditions present during TDD MIMO operation. The components, like Power Amplifiers (PA), filters, etc. present in the device's Tx and Rx paths may vary with temperature or time (aging). Hence, routinely self-calibrating may update the correction factor for channel reciprocity. FIG. **6** outlines the steps used by the routine self-calibration procedure. Element **610** shows the first configuration and the first step (a) of the 3-step self-calibration. In this step, the calibration signal is set to the regular MIMO signal strength and drives the power amplifier at high power (gain) mode. The receive path includes an extra attenuation to prevent a low noise amplifier from saturating. The received calibration signal is recoded as R_{a_k1} (for Step a, Transmitter **1**, Receiver k). Element **620** shows the second configuration and the second step (b) of the 3-step self-calibration procedure. On this step, the calibration signal is digitally attenuated (e.g., by 20 dB) and drives the power amplifier at low power (gain) mode. The receive path retains the extra attenuation. The received calibration signal is recoded as R_{b_k1}. Element **630** shows the third configuration and the third step (c) of the 3-step self-calibration procedure. In this step, the calibration signal is digitally attenuated (e.g., by 20 dB) and drives the power amplifier at low power (gain) mode. The receive path does not consist of any extra attenuation and operates for regular MIMO operation. The received calibration signal is recoded as R_{c_k1}. Element **640** checks to see if both Tx and Rx paths of the two ant./radios under calibration are calibrated. If not, element **650** shows the transmitter and receiver roles being reversed for the two antennas/radios under calibration and can then go to **610** to repeat the 3-step calibration. If both the Tx and Rx paths are calibrated, procedural step described by element **660** then checks if any other antenna/radio in the device is not calibrated. Element **670** selects one of the un-calibrated antenna/radio to pair with the first calibrated antenna/radio and will then go to procedural step **610** to start the 3-step calibration. If all the antennas/radios needed for MIMO operation in the device are calibrated, the self-calibration is complete. The correction factors for the channel reciprocity may be calculated and updated for future use when needed. Element **680** shows that a timer or that a threshold of a pre-defined condition (e.g., temperature) may be pre-set for repeating the self-calibration procedure to obtain an update on the correction factors.

In the above description, an embodiment is an example or implementation of the inventions. The various appearances of "one embodiment," "an embodiment" or "some embodiments" do not necessarily all refer to the same embodiments.

Although various features of the invention may be described in the context of a single embodiment, the features may also be provided separately or in any suitable combination. Conversely, although the invention may be described herein in the context of separate embodiments for clarity, the invention may also be implemented in a single embodiment.

Reference in the specification to "some embodiments", "an embodiment", "one embodiment" or "other embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least some embodiments, but not necessarily all embodiments, of the inventions. It will further be recognized that the aspects of the invention described hereinabove may be combined or otherwise coexist in embodiments of the invention.

It is to be understood that the phraseology and terminology employed herein is not to be construed as limiting and are for descriptive purpose only.

The principles and uses of the teachings of the present invention may be better understood with reference to the accompanying description, figures and examples.

It is to be understood that the details set forth herein do not construe a limitation to an application of the invention.

Furthermore, it is to be understood that the invention can be carried out or practiced in various ways and that the invention can be implemented in embodiments other than the ones outlined in the description above.

It is to be understood that the terms "including", "comprising", "consisting" and grammatical variants thereof do not preclude the addition of one or more components, features, steps, or integers or groups thereof and that the terms are to be construed as specifying components, features, steps or integers.

If the specification or claims refer to "an additional" element, that does not preclude there being more than one of the additional element.

It is to be understood that where the claims or specification refer to "a" or "an" element, such reference is not be construed that there is only one of that element.

It is to be understood that where the specification states that a component, feature, structure, or characteristic "may", "might", "can" or "could" be included, that particular component, feature, structure, or characteristic is not required to be included.

Where applicable, although state diagrams, flow diagrams or both may be used to describe embodiments, the invention is not limited to those diagrams or to the corresponding descriptions. For example, flow need not move through each illustrated box or state, or in exactly the same order as illustrated and described.

The term "method" may refer to manners, means, techniques and procedures for accomplishing a given task including, but not limited to, those manners, means, techniques and procedures either known to, or readily developed from known manners, means, techniques and procedures by practitioners of the art to which the invention belongs.

The descriptions, examples, methods and materials presented in the claims and the specification are not to be construed as limiting but rather as illustrative only.

Meanings of technical and scientific terms used herein are to be commonly understood as by one of ordinary skill in the art to which the invention belongs, unless otherwise defined.

The present invention may be implemented in the testing or practice with methods and materials equivalent or similar to those described herein.

While the invention has been described with respect to a limited number of embodiments, these should not be construed as limitations on the scope of the invention, but rather as exemplifications of some of the preferred embodiments. Other possible variations, modifications, and applications are also within the scope of the invention.

The invention claimed is:

1. A communication device having a receive path comprising:

a number M antennas and respective radio modules, wherein the M antennas and respective radio modules support N×N multiple-input multiple-output (MIMO) transmissions and receptions, wherein M≥N;

a processor operable in a baseband domain and configured to perform a self-calibration procedure by which a correction factor is computed for a channel reciprocity level, determined by said self-calibration procedure;

a plurality of switches and receive paths in each one of said radio modules, said switches configured to select a receive path for regular MIMO operation or a plurality of receive paths during said self-calibration procedure, wherein at least one of said plurality of receive paths includes a path loss element between the respective antenna and a low noise amplifier (LNA); and

a digital attenuator configured to adjust calibration signals in the baseband domain, wherein the M antennas are configured to alternate transmitting and receiving periods on a single channel according to a time division duplex (TDD) communication protocol, wherein the M antennas are configured to define phases employed in MIMO transmission and selected using information measured at the communication device during the receiving periods based on the channel reciprocity level,

wherein the digital attenuator is further configured to digitally attenuate the calibration signals by an amount that is sufficient to prevent the LNA in one of the plurality of receive paths that is undergoing calibration from saturating,

wherein the communication device is further operable to perform the self-calibration procedure in which a first antenna/radio pair (i and j), (i) acts as a transmitter and the other antenna/radio (j) acts as the receiver during the self-calibration procedure, the self-calibration procedure comprising:

performing the following for each of the two antennas/radios (i and j):

emitting a first calibration signal with a signal strength equivalent to a signal strength used during regular MIMO operation, the receiver using the receive path with the path loss element to prevent the LNA from saturation and recording a received calibration signal R_{a_ji};

transmitting a second calibration signal that is digitally attenuated, the receiver continually employing the same one receive path used in said emitting step and recording a received calibration signal R_{b_ji};

transmitting a third calibration signal that is digitally attenuated, the receiver switch selecting the receive path used for regular MIMO operation and recording a received calibration signal R_{c_ji}; and

reversing roles of transmitter and receiver for the two antennas/radios (i and j) to repeat said self-calibration procedure and recording the measured calibrated signals: R_{a_ij}, R_{b_ij}, and R_{c_ij}.

2. The communication device of claim 1, wherein the processor is configured to perform the self-calibration procedure, in order to adjust for the differences in the transmit path and receive path for all the antenna/radios used in MIMO operation, wherein the correction factor is expressed by ρ_{ij}, which is the weight ratio of antenna i to antenna j for the channel reciprocity level.

3. The communication device of claim 1, further operable to compute the correction factor for the channel reciprocity level by:

performing the following for a calibrated antenna/radio and an un-calibrated antenna/radio pair:

selecting the calibrated and the un-calibrated antenna/radio pair to perform the self-calibration procedure after completing the self-calibration for the first antenna/radio pair; and

repeating the self-calibration procedure until all the antennas/radios to be used for MIMO operations are calibrated.

4. The communication device of claim 3, further operable to compute the correction factor for the channel reciprocity level by:

determining the correction factor for the channel reciprocity level obtained with calibration data for the antennas/radios i and j, wherein said correction factor is expressed by $\rho_{ij}=(R_{a\_ji}*R_{c\_ji}*R_{b\_ij})/(R_{b\_ji}*R_{a\_ij}*R_{c\_ij})$.

5. The communication device of claim 1, further comprising: a timer operable to be preset using said processor to repeat the self-calibration procedure for all the antennas/radios used for MIMO operation by recomputing and updating the correction factors for the channel reciprocity level.

6. The communication device of claim 1, further operable to recompute said correction factor for the channel reciprocity level based on a threshold of a changing condition by:

presetting said processor or other baseband logic to recompute and update the correction factor for the channel reciprocity level when said threshold is met; and

repeating the self-calibration procedure for all the antennas/radios to be used for MIMO operation.

7. A method comprising:

deploying a number M antennas and respective radio modules, wherein the M antennas and respective radio modules support N×N multiple-input multiple-output (MIMO) transmissions and receptions, wherein M≥N;

using a processor to perform a self-calibration procedure;

selecting, from a plurality of receive paths using at least one of a plurality of switches in each radio module, a receive path for regular MIMO operation or a plurality of receive paths during said self-calibration method, and wherein a path loss element is included in at least one receive path between the respective antenna and a low noise amplifier (LNA);

adjusting calibration signals in the baseband domain using a digital attenuator, to compute a correction factor for a channel reciprocity level in a communication device;

alternatively transmitting and receiving with an antenna set for alternating periods on a single channel according to a TDD communication protocol;

defining phases employed in MIMO transmissions for selecting said antenna set based on information measured at the communication device during the receiving periods and the channel reciprocity level;

digitally attenuating the calibration signals by an amount that is sufficient to prevent the LNA in one of the paths that is undergoing calibration from saturating; and

performing the self-calibration procedure on a first antenna/radio pair in which a first antenna/radio pair (i and j), (i) acts as a transmitter and the other antenna/radio (j) acts as the receiver during the self-calibration procedure, the self-calibration procedure comprising:

performing the following for each of the two antennas/radios (i and j):

emitting a first calibration signal with a signal strength equivalent to a signal strength used during regular MIMO operation, the receiver using the receive path with the path loss element to prevent the LNA from saturation and recording a received calibration signal R_{a_ji};

transmitting a second calibration signal that is digitally attenuated, the receiver continually employing the same one receive path used in said emitting step and recording a received calibration signal R_{b_ji};

transmitting a third calibration signal that is digitally attenuated, the receiver switch selecting the receive path used for regular MIMO operation and recording a received calibration signal R_{c_ji}; and

reversing roles of transmitter and receiver for the two antennas/radios (i and j) to repeat said self-calibration procedure and recording the measured calibrated signals: R_{a_ij}, R_{b_ij}, and R_{c_ij}.

8. The method of claim **7**, further comprising: performing a self-calibration procedure with a processor or other baseband logic to adjust for the differences in the transmit path and receive path accounting for all the antenna/radios used in MIMO operation, wherein the correction factor is expressed by ρ_{ij}, which is the weight ratio of antenna i to antenna j for the channel reciprocity level.

9. The method of claim **7**, wherein computing the correction factor for the channel reciprocity level further comprises:

performing the following for a calibrated antenna/radio and an un-calibrated antenna/radio pair:

selecting the calibrated and the un-calibrated antenna/radio pair to perform the self-calibration procedure after completing the self-calibration for the first pair; and

repeating the self-calibration procedure until all the antennas/radios to be used for MIMO operations are calibrated.

10. The method of claim **7**, wherein computing the correction factor for the channel reciprocity level further comprises:

determining the correction factor for the channel reciprocity level obtained with calibration data for the antennas/radios i and j, wherein said correction factor is expressed by ρij=(Ra_ji*Rc_ji*Rb_ij)/(Rb_ji*Ra_ij*Rc_ij).

11. The method of claim **7**, wherein performing the self-calibration procedure further comprises:

presetting a timer using a processor or other baseband logic to repeat the self-calibration procedure for all the antennas/radios to be used for MIMO operation by recomputing and updating the correction factors for the channel reciprocity level.

12. The method of claim **7**, wherein performing the self-calibration procedure is based on meeting a predefined threshold of a changing condition by:

presetting a processor or other baseband logic to recompute and update the correction factor for the channel reciprocity level when said threshold is met; and

repeating the self-calibration procedure for all the antennas/radios to be used for MIMO operation.

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